AN ACCELERATOR TECHNOLOGY LEGACY*

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Abstract

Accelerator technology has been a major beneficiary of the investment made over the last decade. It is the intention of this paper to provide the reader with a glimpse of the broad nature of those advances. Development has been on a broad front and this paper can highlight only a few of those. Two spin-off applications will be outlined - a concept for a compact, active, beam probe for solar body exploration and the concept for an accelerator-driven transmutation system for energy production.

RFQ Development

We are all familiar with the RFQ, invented by the Russians, but adopted and highly developed in the West. I start by reminding us that the RFQ is the only significant accelerator component that has been to space and point to BEAR, Beam Experiment Aboard Rocket shown in figure 1. At the time of that experiment in 1989 [1] RFQs were rather short. The BEAR RFQ at 1m length and 1 MeV was not untypical of the genre. This RFQ was rugged and a significant development to make it so was was the use of electroforming to join the RFQ segments.

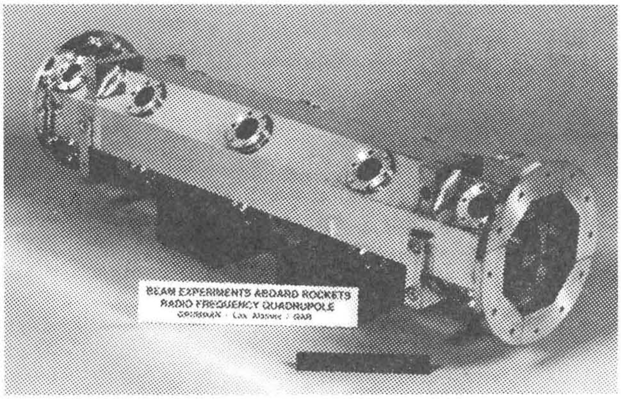

Figure 1. The BEAR RFQ, 1 m long and 1 MeV energy, was typical of those built in the mid-eighties.

The development of RFQs continued well beyond BEAR and included the development of a cryogenic aluminum RFQ [2] for the Ground Test Accelerator (GTA) which showed that such devices could be built to maintain tolerances and operate effectively at 20-30 Kelvin. This was rather long at 2.8 m and energy 2.5 MeV. This was followed by development of a similar structure for CW operation with deuterons (CWDD) which was built by Grumman for operation at Argonne National Laboratory [3] and was of similar size and cryogenic performance. While the GTA and CWDD linacs were being commissioned, effort was turned towards the SSC RFQ [4]. This RFQ benefited from the GTA and CWDD experience in that it included the effects of high order fields and image charges in the design and resulted in significantly improved predicted beam dynamics performance, in transmission particularly. This performance was verified by measurement early this year.

A recent important development is that of Young et al [5] who has now moved the design space to a regime where precision stable RFQ structures can be made almost indefinitely long. Figure 2 shows an eight meter cold model. The invention that enabled this breakthrough was resonant coupling that, in effect, divides the RFQ into virtually discrete coupled segments.

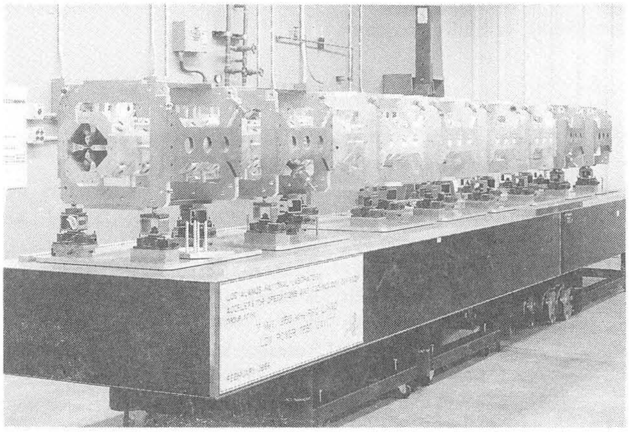

Figure 2. An eight meter long RFQ cold model where the resonant coupling concept was verified.

Combined with this, effort has recently been applied to developing a cheaper means of assembling RFQs while maintaining the high tolerances needed. This work has shown that brazing can be used very effectively to replace the more expensive electroforming technique used on BEAR and CWDD but still result in high quality performance. This is reported at this conference [6].

Drift-tube Linac Development

Drift-tube linac technology had remained fairly stable until the development of GTA. [7]. This required movement to higher frequency (850 MHz) and increased

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precision. Figure 3 shows a segment of the GTA DTL. The drift tubes contain permanent magnet quadrupole magnets which preserve their field strength and low harmonic content at cryogenic temperatures. Mechanical alignment of these drift tubes to +/- 1 mil were achieved as shown in figure 4.

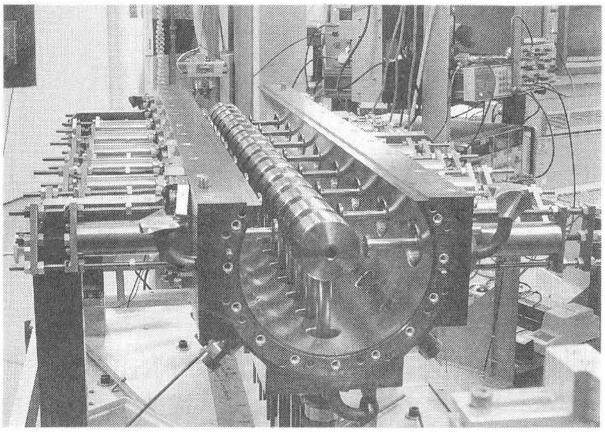

Figure 3. GTA 850 MHz drift-tube linac module.

In addition, the electrical precision, of both the field and field gradient, were very tightly controlled. Both the mechanical and electrical tune up of these modules were very highly automated.

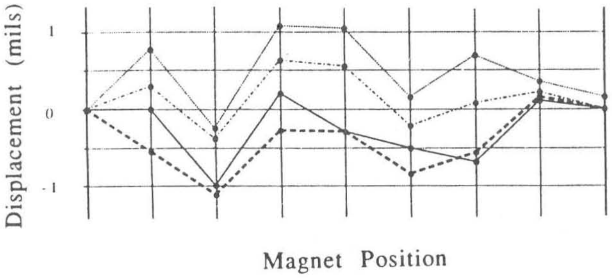

Figure 4. Taut wire alignment of drift tubes (via permanent magnets) gives +/- 1 mil precision.

The use of permanent magnets in CW applications has been of some concern and has led to a return to consideration of electromagnets. This led to invention of the bridge-coupled drift-tube linac [8] which allows focusing elements to be placed between the drift-tube tanks. Such a system has the advantage that access to the drift tubes is preserved for maintenance or replacement. However because the drift tubes tanks are now, in effect, much longer coupled assemblies, tuning and stabilization become difficult.

Overcoming this tuning difficulty resulted in a second invention -- the coupled-cavity drift-tube linac [9]. Here all the advantages of the CCL in tuning are preserved but easy access to the drift-tubes is lost. An important advantage of the CCDTL is that it bridges the gap between the high shunt impedance of the DTL at low energy and that of the CCL at high energy. Figure 5 compares the three geometries for a system at 75 MeV.

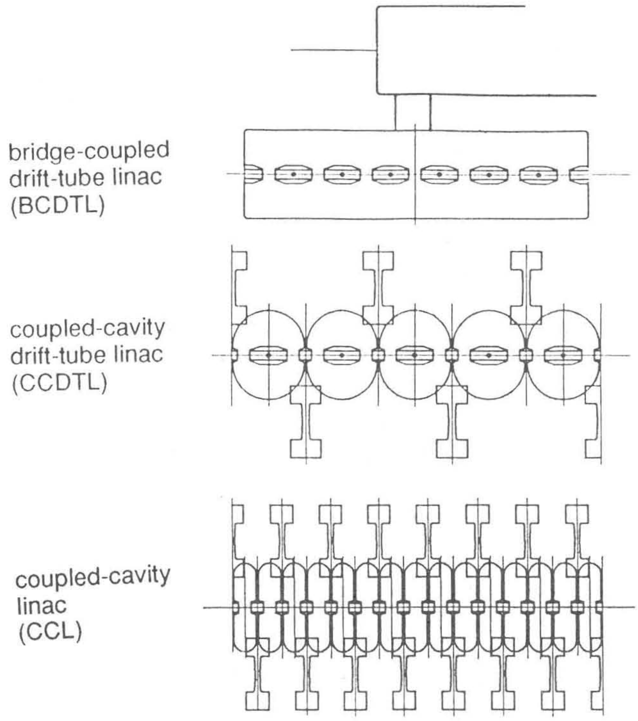

Figure 5. Comparison of different accelerator concepts for intermediate energies.

The combination of the extension of RFQ technology to long lengths and higher energy with the invention of the coupled cavity drift-tube linac has added great flexibility to the design of high performance linear accelerators.

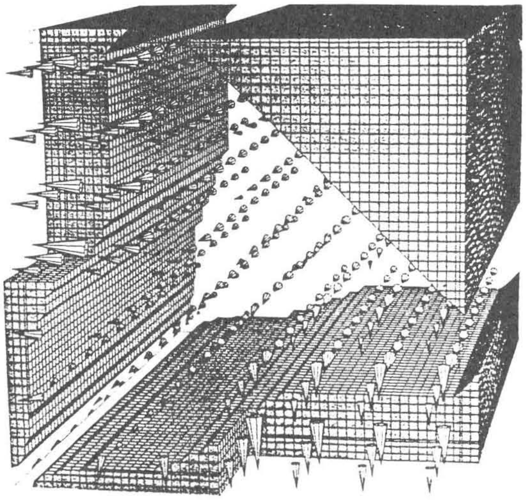

Figure 6. MAFIA field plot for an RFQ end-region.

In passing it is very important to note that design codes have kept up with the engineering [10], [11]. Three-dimensional effects such as RFQ end regions (figure 6) or special cavities such as spoke resonators can be designed fairly routinely using codes such as MAFIA.

High Order Beam Transport

A significant need for advanced beam transport systems has been the development of high order beam-optics systems where the aberrations are corrected. Tools are now well developed which can be applied to any application. Just as an illustrative example I show a PARMILA output for a system (figure 7) where octupole and docecapole elements were used to flatten a beam distribution [11]. Such systems are useful for both the transmutation application to be described later but to such devices as industrial irradiators.

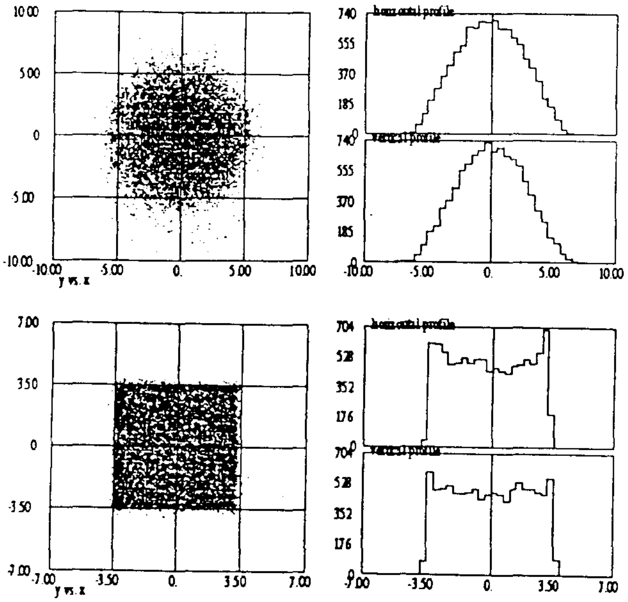

Figure 7. High order flattening of a beam distribution with octupole and dodecapole elements.

Controls

Controls of course have continued to advance most rapidly. One system, EPICS [13], is enjoying very widespread acceptance, and is now in use at an astonishing 26 systems world-wide. This client-server-based system with its distributed control and information capability allows expansion of capability with immediate compatibility with what already exists. Collaborating institutions have access to source code and can work largely independently but yet easily access and use what others have developed.

The prominent features attractive to the accelerator community are the ability to serve both many I/Os and many devices; that screens are updated fast and efficiently; and that the system is really real time i.e. operations can be synchronized to milliseconds.

Controls extends beyond software and architecture to the actual hardware. Developments in the rf arena are decribed elsewhere in this conference [14]. They include adaptive feedforward, which has been very successfully developed and an example of its capability in a pulsed rf system is shown in figure 8.

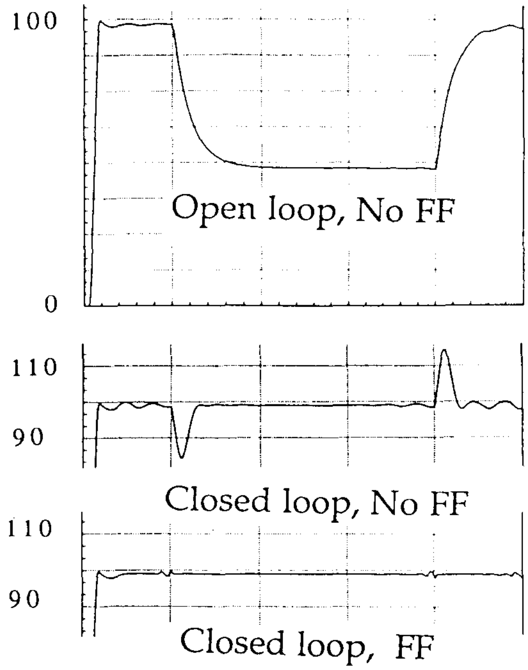

Figure 8. Illustration of successful application of adaptive feedforward to pulsed rf control.

Applications

Linear accelerator technology has matured significantly in the last decade and applications considered are diverse. I have selected only two that I believe may be of special interest.

Solar Body Probe

A significant element of recent study has been consideration space options and much work was in fact expended to examine the feasibility of a space probe for exploration. The specific objective was to consider direct mineral prospecting capability on the moon which could be extended to other solar system bodies. This effort was led by the then Grumman Corporation and the science of the mission is nicely reviewed in a paper by Meinel et al. [15] of Science Applications International Corporation, a partner in the study.

The device required for such a mission is quite modest in performance -- 5 MeV energy and 12 mA neutral current at about 1% duty factor. The actual accelerator beamline and delivery system is 12 m long and would weigh about 1.5 tonnes of the total payload of about 6.2 tonnes. It was proposed to use the Russian Proton launch vehicle which is a very good match to requirements. The beamline is shown in figure 9.

The primary diagnostic tool is proton-induced x-ray emission or PIXE. Protons striking the lunar surface excite the atoms and the emitted characteristic K and L-shell x-rays (several keV) indicate the presence of key elements such as Mg, Al, Si, Ca, Ti, and Fe.

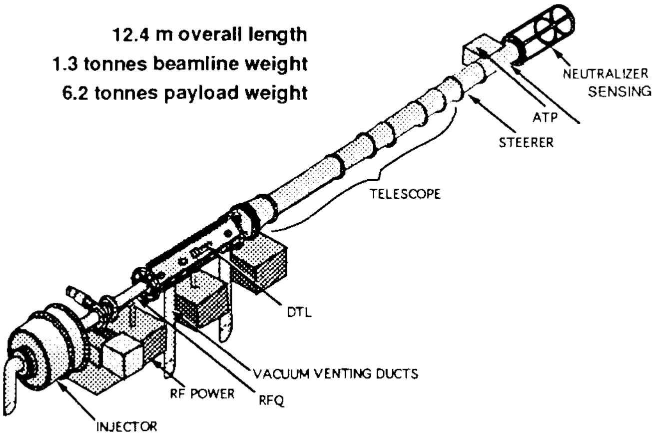

Figure 9. Layout of beamline for proposed probe for active lunar exploration of selected targets

The abundance of these elements can be measured to better than 10% precision. The resolution obtainable on the surface is about 100m from a polar orbit at about 50 km altitude. In addition to this active sensing at selected targets, a global map of the same six elements across the lunar surface can be made by measuring the yield from cosmic ray-induced x-rays. The concept is shown in figure 10.

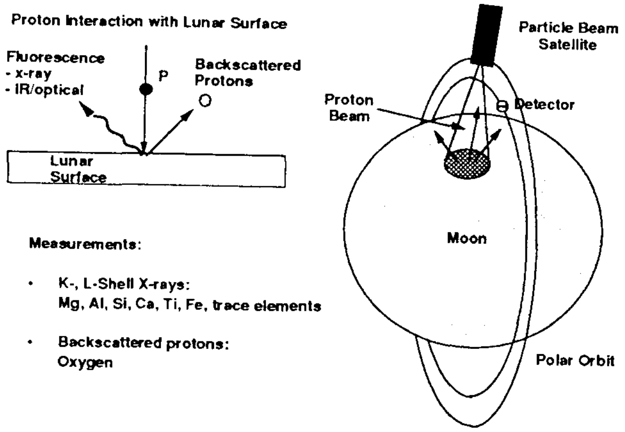

Figure 10. Probe concept is to detect proton induced x-rays detected by coorbiting detector satellite.

The specific targets designated for detailed probing would be pyroclastic deposits; dark-haloed craters; young crater walls, peaks and ejecta blankets; and bright-swirl features. The science themes explored are formation of the Earth-Moon system, thermal and magmatic evolution of the Moon and bombardment history of the Earth-Moon system.

Accelerator-Driven Transmutation

One of the most exciting applications of accelerators that is currently receiving a lot of attention is the so-called accelerator-driven transmutation technology. The recent Conference in Las Vegas [16] highlighted the several technical options and issues in considerable detail.

Fundamentally the system works as follows and as described in figure 11. An accelerator creates an intense source of spallation neutrons at the center of a target-blanket by bombarding a heavy metal target with high energy protons. At high proton energies (around 800 MeV) about 20 to 25 neutrons are produced per incident proton. The target-blanket is a fissile-fueled but subcritical neutron multiplication assembly with multiplications of typically 20 to 50. When the accelerator beam is switched off the system shuts down.

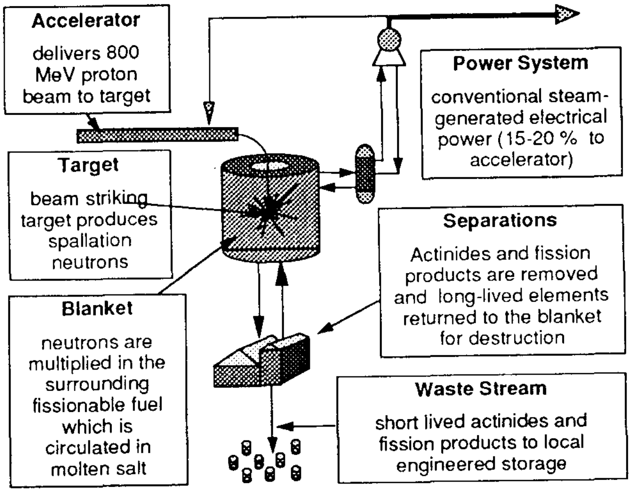

Figure 11. Molten-salt accelerator-driven energy producer concept based on the thorium/uranium cycle.

While such applications have been investigated for many years, it is the developments in accelerator technology like those in this paper that, in large measure, have renewed interest and provide increased confidence that the required accelerator technology can be built.

A more distant option is to use such a system to produce electrical energy and I will briefly describe the concept developed by the transmutation group at Los Alamos. Figure 12 shows a target-blanket assembly comprising a molten-lead target surrounded by a thorium-bearing molten-salt fuel which flows in a graphite moderator lattice. Since the thorium is fertile (absorbs neutrons to form the fissile U-233) but not fissile, it must be augmented by a small amount of enriched uranium to start the cycle.

A very interesting feature of this system is that it produces little or no actinides, including plutonium, as shown in figure 13. Even the uranium isotopes in the system are never produced in forms attractive for weapons but are diluted with the non-fissile isotopes and so would require isotopic separation for any extraction of weapons material.

The system concept would allow an 800 MeV 90 mA accelerator to drive six modular 500 MWt target-blanket assemblies which in turn produce enough deliver around 1 GWe to the grid.

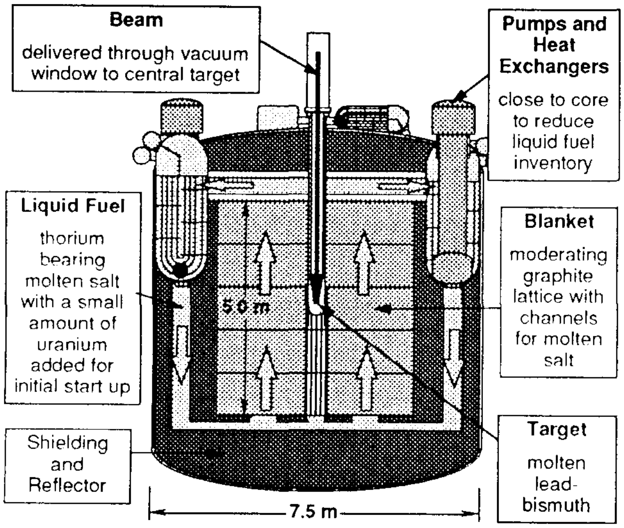

Figure 12. Target-blanket concept for an accelerator-driven transmutation system.

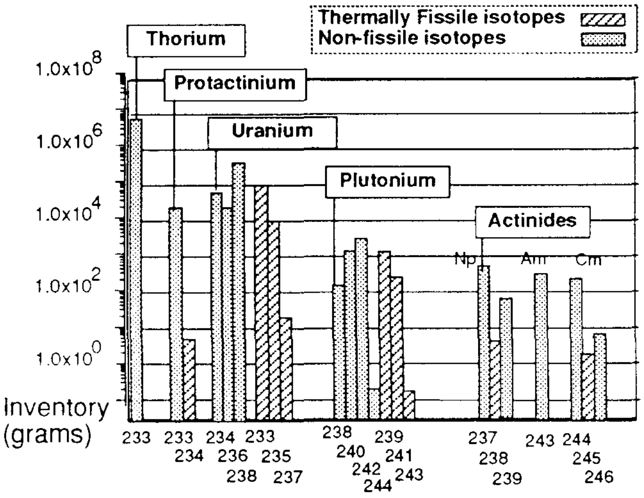

Figure 13. Spectrum of actinides produced in a thorium-fueled energy producer.

Summary

The last decade has given the linear accelerator community increased confidence that it can build advanced accelerators to high precision and performance for several applications. The few advances outlined here only touch on the scope of the technology. The applications beyond the two briefly described are several. It is to be hoped that the next ten years will see some of these interesting applications come to bear fruit.

Acknowledgments

This paper describes the work of too many to list here. Therefore, to those who gave me lots of input and advise and data - I say many thanks. Our technology is strong and healthy because of your work.

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